The future of satellite magnetic anomaly studies is bright!

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Magnetometers aboard satellites (e.g., POGO and Magsat) have recorded anomalies that provide a unique perspective on the thermal regime and the nature, thickness, and evolution of the earth's lithosphere; as a result, these anomalies aid in the identification of geologic provinces of interest in petroleum and mineral exploration. The literature regarding the uses of satellite magnetic anomalies is vast, but the daunting task of summarizing it was achieved in a recent book by Bob Langel and Bill Hinze.

The present data (~400 km elevation) have near global coverage and give useful information at long wavelengths (~500-3000 km), the part of the spectrum in which data from conventional aeromagnetic surveys are incomplete. Because longer wavelengths contain information from deeper sources, the data have increased our awareness of the strong magnetization of lower crustal rocks and contributed to our fundamental understanding of the magnetization of the upper mantle. As we show in this short article, the individual strengths of aeromagnetic and satellite data may be combined into a more effective and complete spectrum of the anomaly field. Moreover, upcoming lower-altitude satellites will record anomalies with better resolution and significantly greater amplitudes.

The global depth-integrated susceptibility map. Because POGO and Magsat satellites measured the magnetic field far away from the anomaly sources, the data usually are not suitable for deciphering source geometry. However, the magnetic field observations can be described in terms of depth-integrated magnetic properties of the lithosphere.

The susceptibilities mapped in Figure 1 and their variations can be interpreted as cumulative magnetic effects within and across neighboring large-scale tectonic provinces due to tectonic features such as subduction zones (e.g., Kuril-Kamchatka trench) and to variations of the heat flow (e.g., the western United States). Some very intense high-susceptibility regions also correspond to known regionally extensive magnetic ore deposits (e.g., Kursk iron formations, although the known ores are only one contributor to the high magnetic properties or intensity of anomalies). Very low-susceptibility regions, on the

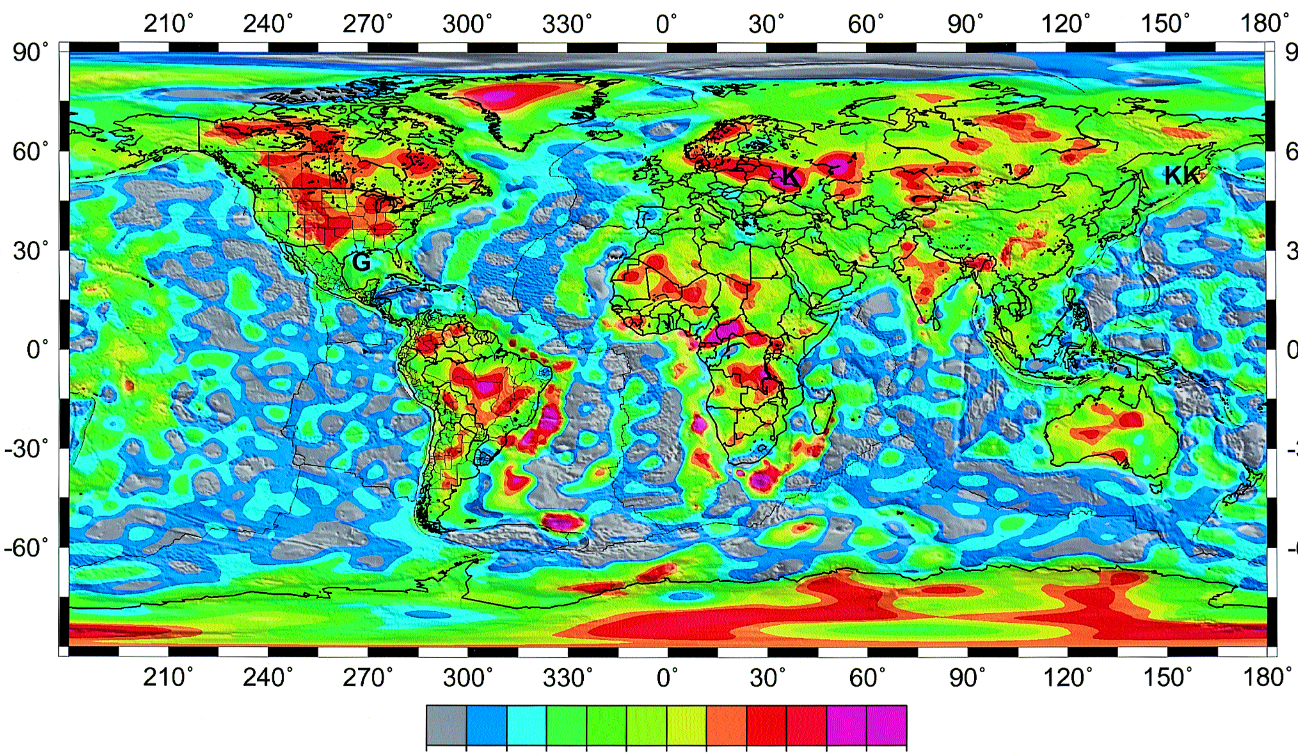

Figure 1. A depth-integrated magnetic susceptibility map of the world. K=Kursk region; G=the U.S. Gulf Coast; KK=Kuril-Kamchatka trench. The magnetic field is draped over gray-shaded topography and bathymetry. This map is constrained at continental scale by seismic information regarding the thickness of the igneous crust, heat flow, and gross crustal types such as continental crust, transitional crust, the oceanic crust and, at more local scales, by Magsat observations. Units are susceptibility, in SI units times thickness in km times 10. The magnetic field calculated from this map, after removal of spherical harmonics corresponding to the main field, matches that of the Magsat anomaly field of Cain et al. (1990). These calculations assume magnetization by induction only. In the future, we will take into account the effect of induced and remanent magnetization in the oceanic regions.

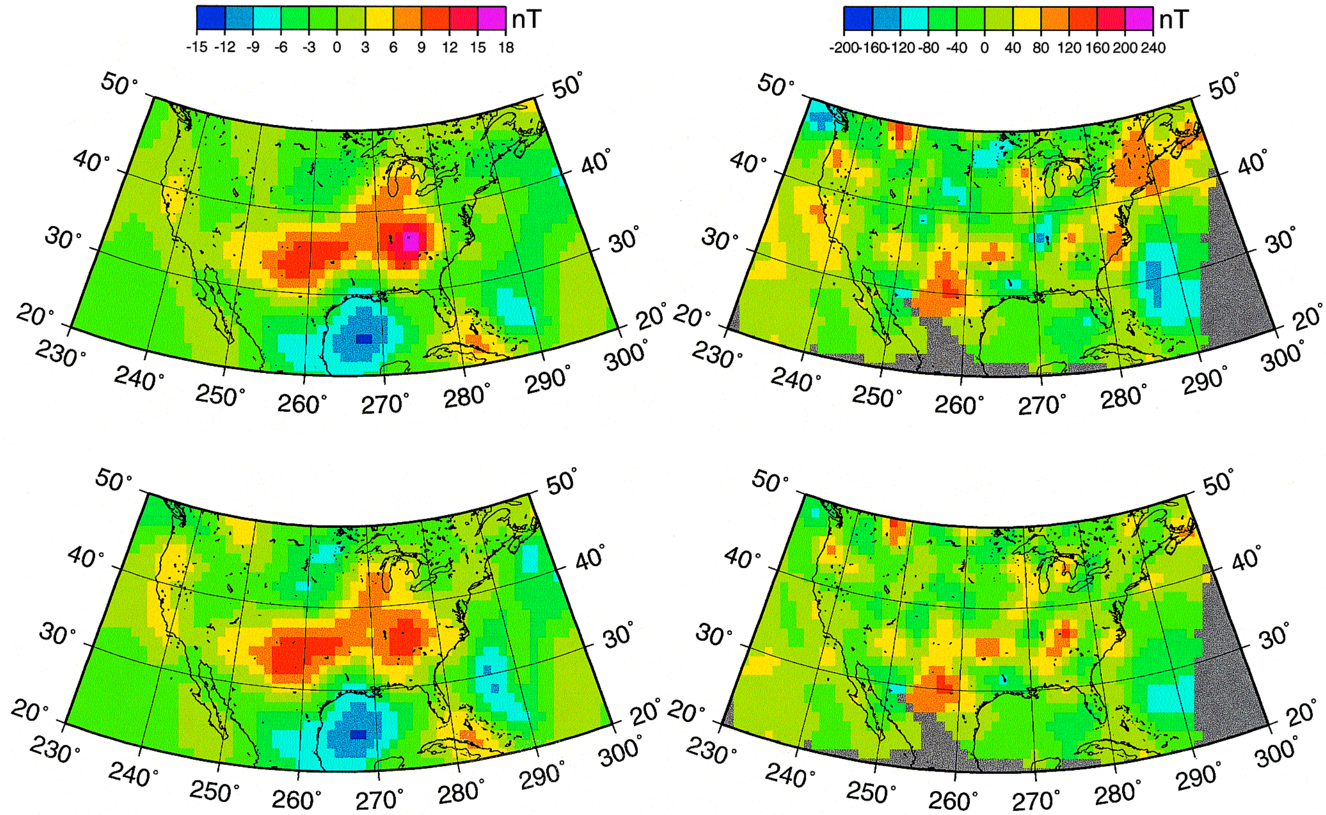

Figure 2. If one can find a single set of equivalent sources that can represent potential fields at distinctly different elevations, then those fields must be considered compatible with one another. A comparison of the "observed" anomaly fields (top) and the fields computed from a jointly-inverted set of equivalent dipoles (bottom) shows that, to a large extent, the Magsat anomalies and the DNAG aeromagnetic anomalies are compatible. The observed and the computed Magsat anomalies (the two subfigures on the left) have a good spatial correlation with each other (correlation coefficient of -0.92). Similar comparison for the DNAG counterpart yields a correlation coefficient of -0.90 (the two subfigures to the right). The Canadian data mentioned in the text were more compatible (correlation coefficients of -0.95 at both aeromagnetic and satellite altitudes). More rigorous wavenumber domain comparisons have been made and a manuscript describing these comparisons over Canada is in preparation. Why are only wavelengths >500 km in the DNAG magnetic map compared? 1) All of the aeromagnetic anomalies over the United States and Canada with wavelengths <500 km when analytically upward-continued to 400 km elevation are attenuated to <1nT amplitude. (This is lower than the resolving capability of the present satellite magnetic data at 400 km and, thus, any compatibility or incompatibility in this waveband is meaningless.) 2) The number of equivalent sources needed to represent the wavelengths >500 km is much less than the number required to map fields at short wavelengths.

other hand, reflect large accumulations of weakly or nonmagnetic rocks, remanently magnetized sources, and/or regions of thinner magnetic crust that may include areas of high heat flow (e.g., the U.S. Gulf Coast).

Are airborne and satellite magnetic anomalies compatible? Grauch's 1993 analysis of the continental United States DNAG aeromagnetic compilation in combination with our experience with satellite anomalies shows that these data have varying types of errors; the U.S. compilation has fewer errors in wavelengths of a few kilometers to ~800 km, and the Magsat anomalies have better signal-to-noise ratios at wavelengths greater than 500 km.

So instead of "verifying" anomalies (which involves assuming that one of them is unblemished), we decided to find out whether they are "compatible" with each other. Recently, we tested such compatibility using a joint equivalent-source inversion of the Magsat data and the Canadian high-altitude aeromagnetic surveys. Figure 2 presents the results for a portion of the DNAG aeromagnetic compilation.

The comparison of the long-wavelength observed anomalies and the anomalies computed from a single set of dipoles derived from the inversion is quite remarkable, especially since the data sets are separated in elevation by 400 km. We expected positive results over Canada because of earlier comparisons with similar data by Pilkington and Roest, but we did not expect the long-wavelength U.S. comparisons to look as good as they do in Figure 2.

In the observed and jointly inverted long-wavelength DNAG maps, the regions of severe disagreement straddle the eastern and western coasts of the United States (other disagreements are relatively small). Because satellite data is more homogeneously collected and compiled than the continent-scale aeromagnetic compilation of the United States, any lack of compatibility between the data sets indicates problems in the DNAG map. Comparison of the results over Canada and the continental United States reveals that the two fields are indeed compatible, but there are more disparities over the United States.

Adjusting the long-wavelengths of the aeromagnetic

quilts. In order to "adjust" the long-wavelengths of the DNAG compilation, we simply add the short-wavelength (< 500 km) anomalies of the DNAG map to the field computed at the aeromagnetic level from the joint equivalent source inversion (that is, add to the bottom right part of Figure 2). This is acceptable because the fields in Figure 2 are made from "compatible" information—a combination of Magsat and the long-wavelength (> 500 km) DNAG aeromagnetic map. A preliminary result of this merger is at the bottom of Figure 3; the original DNAG compilation is at the top of Figure 3. (Actually, there are a number of different ways to achieve the adjustments, and we are currently comparing different strategies and analyzing their advantages and limitations.)

Long-wavelength adjusted aeromagnetic compilations are certainly useful to arm-waving geophysicists (actually, despite our sarcasm, we do find these compilations immensely conducive to new ideas and mentally continuing the geology from one region to another). But, the most important quantitative advantage of the corrected long wavelengths in the aeromagnetic data is the control on the deeper magnetic materials in the earth's lithosphere. A useful example from this perspective for the genesis of resources would be the better control possible on the Curie depths. Future lower-altitude satellite missions will be able to constrain even shorter wavelengths (to roughly 250 km, depending on how well we can remove ionospheric "noise")—and that brings us to the future!

A glimpse of the future. Table 1 lists past, present, and upcoming satellite missions that have had or will have indirect or direct bearing on the mapping of magnetic anomalies. Of direct importance is the German mission CHAMP because it will spend some time at 250 km. What will the magnetic anomalies look like at this elevation? Fortunately, we are in a position to answer that question over some

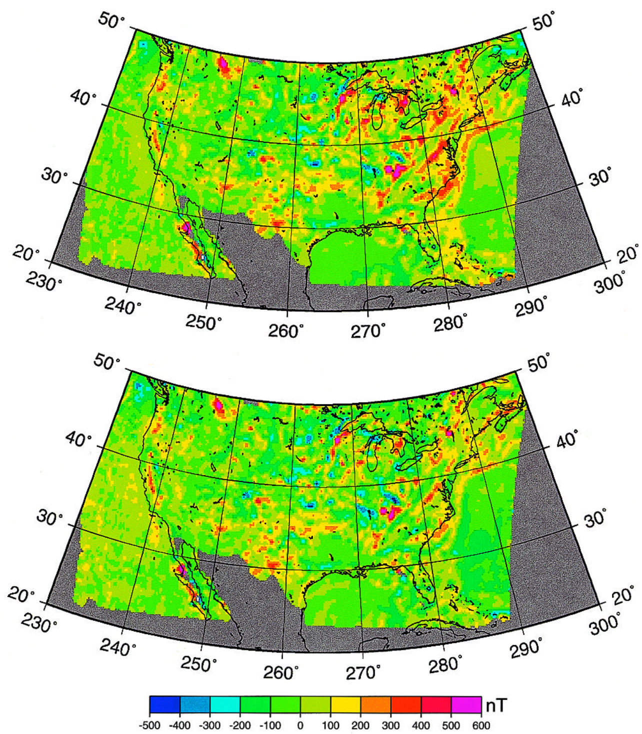

Figure 3. Preliminary leveled U.S. portion of a coarsely sampled (0.20) DNAG aeromagnetic grid (bottom). Wavelengths <500 km (tapered from 400 to 600 km) are from the DNAG grid; wavelengths >500 km are from the jointly-inverted DNAG field in Figure 2 (bottom right). For comparison, the original DNAG grid (at 0.20 spacing) is also shown (top). The eastern third of the U.S. appears most affected by this processing at this scale. What is the reason behind the difference? Probably because some surveys in the east are the oldest surveys in the United States and when these surveys were brought into the compilation their levels were not accurately known (e.g., the main field was not known as precisely for the old surveys as it is today).

Table 1. Various satellites pertinent to mapping the magnetic anomaly field of the earth.

Satellite /Country	Orbital inclin.	Altitude	Dates	Instruments	Achievable precision for anomalies	Uses
OGO-2 (POGO) /USA	87°	413-1510 km	1965-67	Rubidium (Scalar)	2 nT	crustal & main field
OGO-4 (POGO) /USA	86°	412-9080 km	1967-69	Rubidium (Scalar)	2 nT	crustal & main field
OGO-6 (POGO) /USA	82°	397-1098 km	1969-71	Rubidium (Scalar)	2 nT	crustal & main field
Magsat /USA	97°	3253-550 km	1979-80	Fluxgate & Cesium	3 nT (vector 1-2 nT (scalar computed from vector)	crustal, main, & ionospheric field
Ørsted /Denmark	96°	620-850 km	1999-2000	Fluxgate & Overhauser	2 nT (vector) 1 nT (scalar)	main & ionospheric field
CHAMP /Germany	83°	250-470 km	1999-2004	Fluxgate & Overhauser	2 nT (vector) 1 nT (scalar)	crustal, main & ionospheric field
SAC-C /Argentina	98°	702 km	2000-2004	Fluxgate & Helium	4 nT (vector) 2 nT (scalar)	Main & ionospheric field

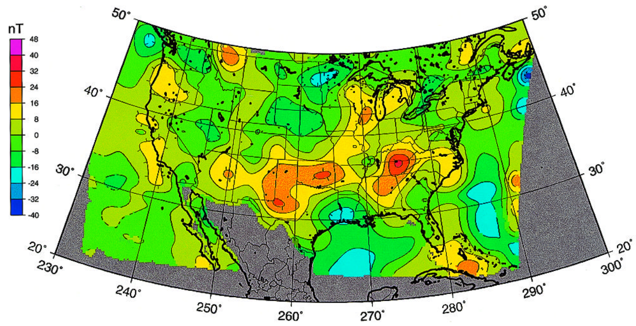

Figure 4. Scalar anomalies at 250 km over the United States and vicinity computed from the jointly inverted equivalent-source configuration. Analytical upward-continued (to 250 km) short-wavelength anomalies (wavelength <500 km) have been added to retain the short-wavelength end of the anomaly spectrum. The short-wavelength DNAG anomalies amount to less than 5 nT at 250 km and are masked by larger-amplitude long-wavelength anomalies.

regions of the world. Because of the capability of jointly inverting the satellite and aeromagnetic maps to a common set of equivalent sources (Figure 2), we can accurately compute the long wavelengths of the anomaly field anywhere between the elevations of the two data sets. Figure 4 is the result at 250 km over the United States.

This figure also includes (through simple addition) an analytical upward continuation (to 250 km) of anomalies shorter than 500 km from the DNAG map (to avoid missing any information from the high-wavenumber end of the anomaly spectrum). Although the shorter-wavelength detail in the figure is masked by larger-amplitude longer-wavelength anomalies, the figure illustrates what future satellite missions will show over the rest of the world.

The next century will most likely see instrument packages that use space tethers, observe magnetic gradients, and coordinate multiple satellites in orbit at the same time (to constrain the modeling of ionospheric fields to better isolate crustal magnetic anomalies) and more. All these advances will improve the resolution of the anomalies and will make these global sets of data important tools in integrated geologic interpretation.

Suggestions for further reading. "Limitations of the long-wavelength components of the North American magnetic anomaly" by Arkani-Hamed and Hinze (GEOPHYSICS, 1990). "Numerical experiments in geomagnetic modeling" by Cain et al. (*Journal of Geomagnetism and Geoelectricity*, 1990). "Limitations on digital filtering of the DNAG magnetic data set for the conterminous U.S." by Grauch (GEOPHYSICS, 1993). *The magnetic field of the Earth's lithosphere: the satellite perspective* by Langel and Hinze (Cambridge University Press, 1998). "An assessment of long-wavelength magnetic anomalies over Canada" by Pilkington and Roest (*Canadian Journal of Earth Sciences*, 1996). "Global magnetization models with a priori information" by Purucker et al. (*Journal of Geophysical Research*, 1998). "Recent advances in the verification and geologic interpretation of satellite-altitude magnetic anomalies" by Ravat et al. (SEG 1998 *Expanded Abstracts*).

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